The effects of installation procedure on bond characteristics of fully grouted rock bolts

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Abstract

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ABSTRACT

The bond characteristics of fully grouted rockbolts installed in steel tubes were investigated by bolt push tests. Steel tubes were inserted in a mine roadway roof to represent the confinement of rock boreholes. Rockbolts were installed in tubes using the installation technique of Australian underground mines. These tubes, with rockbolts inside, were retrieved from the field and brought back to the laboratory to be cut into 100-mm sections, which were then push tested. It was found that each bolt section had a distinct load-displacement profile, and that bond strength varied significantly along the bolt length. The factors influencing the bond strength of rockbolts were identified. The influence of the installation procedure on the bond strength of bolts in tubes was investigated.

Keywords

fully grouted rockbolts, push tests, Spin to Stall, Spin and Hold, bond strength

Introduction

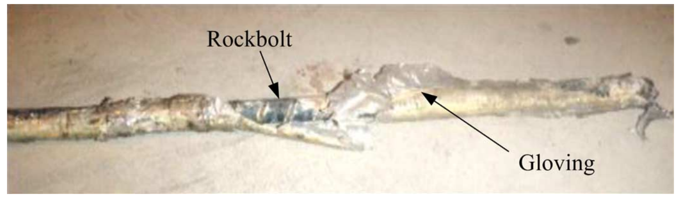
The installation of rockbolts in a fractured rock mass could improve the inherent strength of the rock. The load is transferred between the bolt system and the rock borehole during rock strata deformation. The load transfer capacity (i.e., the interfacial shear bond strength) of fully resin-encapsulated rockbolts could significantly influence the stability of a bolted rock mass.

For fully grouted rockbolts, shear bond stress is mobilized at the bolt-grout interface and the grout-rock interface when the reinforced rock mass deforms. The load is transferred between rockbolts and rock mass by the grout. Failure of a rockbolt system under tension might be due to the failure of bolt material, or the bolt-grout interface breakage and the grout-rock interface breakage, depending on which one of the failure modes is the weakest. The relationship of the interfacial shear stress and the relative displacement between the bolt and rock mass is often termed as "bond-slip relationship," which could affect the bolt performances.

Various bond-slip relationships have been presented and applied in numerical methods (Ivanović and Neilson 2009; Nie et al. 2014a, 2014b; He et al. 2014; Deb and Das 2010, 2011a, and 2011b; Nemcik et al. 2014; Ma et al. 2016) and analytical studies (Li and Stillborg 1999; Ren et al. 2010; Martin et al. 2011a;

FIG. 1

Gloved rockbolt overcored from a mine (Craig 2012).



Ma et al. 2013, 2014; Chen et al. 2015). Ivanović and Neilson (2009) proposed a lumped parameter model for fully grouted rockbolts, in which the bilinear and trilinear bond-slip relationships were implemented. Deb and Das (2011a and 2011b) simulated the axial behaviours of rockbolts by implementing the trilinear bond-slip curve into enriched finite element method. Nemcik et al. (2014) introduced the nonlinear bond-slip relationship into Fast Lagrangian Analysis of Continua, wherein the modified rockbolt elements are able to model the decoupling failure process. For analytical studies, Ren et al. (2010) and Martin et al. (2011a) presented their respective analytical models for fully grouted rockbolts subjected to tensile loading. These analytical models took into account the trilinear bond-slip relationships. Ma et al. (2013) proposed an analytical rockbolt model, in which a nonlinear bond-slip relationship was considered.

Laboratory tests have been used to study the bond characteristics of bolts (Benmokrane et al. 1995; Kilic et al. 2002, 2003; Aziz 2004; Martin et al. 2011b; Chen and Li 2015; Li 2012; Chen et al. 2016). However, the bond characteristics of bolts in these laboratory tests cannot realistically represent rockbolts in the field. The laboratory tests do not take into account the effects of the resin cartridge film, machinery (the equipment used to install rockbolts), and the bolt installation procedure. These factors could influence the performance of rockbolts.

Lutz and Gergely (1967) pointed out that the bond strength of fully grouted rockbolts is dominated by the mechanical interlock between resin and bolt ribs, and resin and borehole irregularities. The poor resin mixing and gloving are common issues encountered in the field (Compton and Oyler 2005) and could result in weak resin strength and poor rockbolt performance. Resin cartridge film can be broken down, after which the resin is mixed with the catalyst in the rockbolt installation process. The term "gloving" refers to the phenomenon when the resin cartridge sheath does not shred but spreads along the resin encapsulation annulus and remains wrapped around the rockbolt. Gloving could weaken the interlocking mechanism between bolt profiles and the borehole irregularities, therefore reducing the loading capacity of rockbolts. Campbell et al. (2004) found unmixed resin at the location of gloving, where it occurred at a range of 30 mm to 790 mm along the rockbolts. Pastars and MacGregor (2005) carried out in situ and laboratory pull tests to study the effects of the gloving. They concluded that gloved bolts can only generate approximately 10 % of the load capacity, in comparison with the non-gloved bolts. Craig (2012) investigated gloving issues by overcoring the rockbolts installed in a coal mine. He showed that gloving occurs at more than 50 % of their length, as shown in **Fig. 1**.

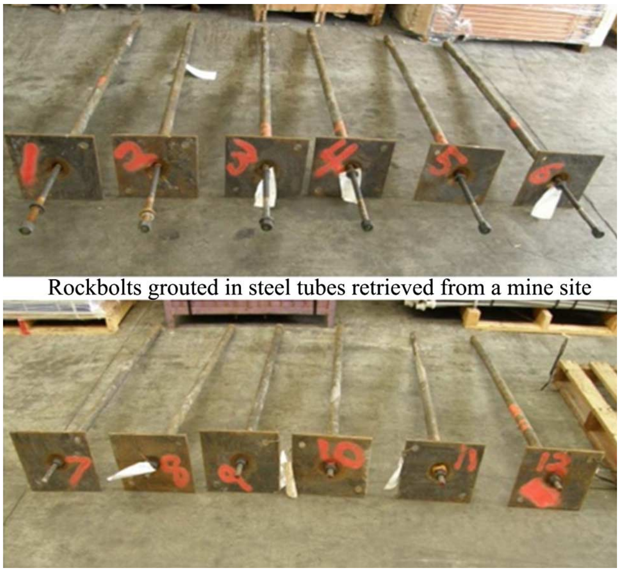
The installation quality of rockbolts associated with the installation procedure and the machinery can also affect the performance of the bolting system. The commonly used installation method of rockbolts in Australian coal mines is the Spin and Hold method, in which the bolt is spun through the length of the resin capsule for approximately 75 % of the "spin time," and when the bolt reaches the back of the borehole, continues to spin for around 25 % of the spin time (Hillyer et al. 2013). In the following "hold time," the operators stop spinning and the fast-set resin in the upper section of the bolt hardens. After that, bolts are pretensioned by fastening the bearing plates against the rock. Another installation method is the Spin to Stall technique in which the operators continually spin the bolt at the beginning of the installation, until the shear pin breaks, and then tighten the nut against the plate. This installation method was pioneered by Goedehoop Colliery of South Africa (Bugden et al. 2001). This method might reduce the resin strength due to overmixing. The advantage of using this method is its ability to eliminate the hold time and improve productivity of coal mines.

Very few studies have been conducted to investigate the bonding characteristics of fully resin grouted rockbolts installed in the field using the resin capsule, and to examine the effects of film gloving and installation methods on the performances of rockbolts. Altounyan et al. (2003) investigated the effects of spin time on bond strength. They installed rockbolts into 800-mm long, 27-mm inside diameter threaded steel tubes using resin capsules. These tubes were cut into 100-mm-long sections, and each section was tested by pushing the bolt out of the tube. It was concluded that spin time could impact the bond strength of rockbolts, and that the reduction of the bond strength at the top of the bolt is related to film gloving. The current study used methods similar to the research of Altounyan et al. (2003), with the objective to investigate the bond strength of rockbolts installed in the field.

Push Tests of Steel Tube Sections

The authors conducted laboratory tests to study the bond characteristics of fully grouted rockbolts at the University of

FIG. 2 Twelve bolts grouted in steel tubes retrieved from a mine site.



Wollongong (UOW). Steel tubes were used to simulate the rock borehole condition. The outer/collar end of each steel tube was welded to a 300 mm by 300 mm steel plate, with the other end blanked off by an end cap. These steel tubes were placed vertically into holes with 64-mm diameters, which were predrilled in a local underground mine roof. The tubes were internally threaded, with an internal diameter of 28.5 mm and wall thickness of 9 mm. The used M24 rockbolts measured 1.7 m in length and 23.7 mm at full diameter, with a solid core diameter of 21.7 mm. Bolts were installed in the steel tubes using standard rockbolt installation procedures as normally used in Australia underground mines.

The tube installation was conducted at Baal Bone mine, which is located in the western coalfields of New South Wales, 32 km north of Lithgow and roughly 130 km from Sydney. Baal Bone mine is closed and only used for research. A 64-mm-hole was drilled into the roof strata, which was 1.7 m in length). The tubes were inserted into the boreholes. The used resin had the uniaxial compressive strength (UCS) of 71 MPa and a shear strength of 16.2 MPa. For the steel tubes, the Young's Modulus was 200 GPa and ultimate tensile strength (UTS) was 400 MPa. The host rock was mudstone with UCS of 33 MPa, Poisson ratio of 0.26, and Young's Modulus of 5 GPa.

After installation, the steel tubes were retrieved from the underground mine and transported to the UOW for further testing and evaluation. **Fig. 2** shows the steel tubes with rockbolts, retrieved from the mine site. **Table 1** shows the installation details of these rockbolts.

Tests Nos. 1 and 2 used Jennmar X-grade steel bolts with 12 mm rib spacing (JBX) and Minova-supplied resin capsules, whereas for the rest of the tests, Jennmar X-grade steel bolts with 25 mm rib spacing (JX) and Jennmar J-LOK resin were used. JX and JBX bolts are made of the same steel material. Their yield strength is 215 kN and UTS is 315 kN. The installation parameters such as spin time and spin speed were recorded electronically or measured by standard instrumentation by operators. The installation procedure incudes two parts: the "spin to back" time, which defines how long it took for the bolts to be spun through the length of resin capsules to the end of the tubes, and the "spin at back" time, which indicates how long the bolts were spun at the back of the tubes. Bolts 1–6 used the "Spin and Hold" installation method, while bolts 7–12 used the "Spin to Stall" method. Bolts 3 and 4 used the "Spin and Hold" method, which is a commonly used bolt technique in Australian mines. They provide a baseline for comparative studies.

The steel tubes with rockbolts installed inside were cut into 15 sections. Each section was 100 mm long and numbered as shown in **Fig. 3**. The outer 200 mm of the bolt near the plate end was discarded because the bolt was fully anchored to the tube

TABLE 1 Installation details of rockbolts.

			Spin to Back		Spin at Back		
Test No.	Bolt	Resin	Time (s)	Approx r/min	Time (s)		Approx r/min
1	JBX	MN 1,000 mm F/S oil-based resin	10	420	4		450
2	JBX	MN 1,000 mm F/S oil-based resin	10	420	4		450
3	JX	J-Lok 1,000 mm JGD F/S oil-based resin	9	420	3		450
4	JX	J-Lok 1,000 mm JGD F/S oil-based resin	9	420	3		450
5	JX	J-Lok 1,000 mm JGD F/S oil-based resin	6	100	6		100
6	JX	J-Lok 1,000 mm JGD F/S oil-based resin	6	100	6		450
Bolts 7–12 were spun until the pin broke out and bolt tightened to the rig stall					Pin break	Stall	
7	JX	J-Lok 1,000 mm JGD F/S oil-based resin	8	420	28	35	450
8	JX	J-Lok 1,000 mm JGD F/S oil based resin	8	420	29	33	450
9	JX	J-Lok 1,000 mm JGD F/S oil-based resin	6	100	18	22	450
10	JX	J-Lok 1,000 mm JGD F/S oil-based resin	6	100	13	17	450
11	JX	J-Lok 1,000 mm JGD F/S oil-based resin	6	0	10	12	450
12	JX	J-Lok 1,000 mm JGD F/S oil-based resin	6	0	11	14	450

FIG. 3
The 100-mm-long sections of rockbolt/resin/steel tube.

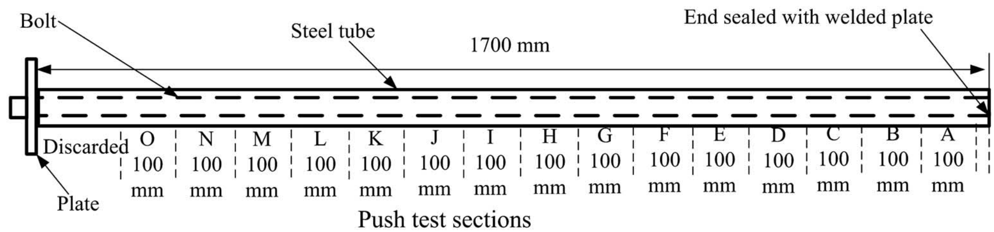
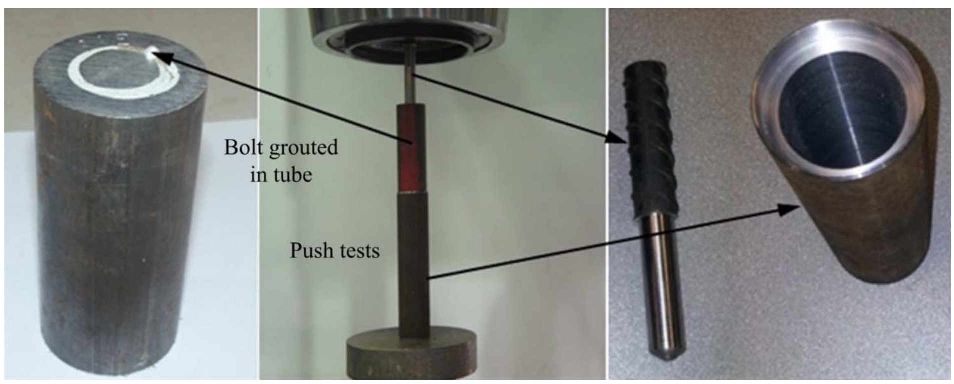


FIG. 4
Bolt push test setup.



due to the lack of resin. The bond strength of each 100-mm bolt section was tested by pushing the bolt out of the pipe using the compressive testing machine. The bolt push test setup is shown in **Fig. 4**.

Results and Discussions

The loading forces and the displacements were monitored during the push tests for each pipe section. There were a total of 150 load-displacement curves resulting from the push tests. The results of Rockbolt 3 were selected and are discussed here. The information of all other tested bolts can be found in Ma (2014).

BOLT 3

The load-displacement profiles of 15 sections of Bolt 3 are shown in **Fig. 5a**. The load-displacement profiles of the top, the middle, and the bottom of Bolt 3 are shown respectively in **Fig. 5b**, **5c**, and **5d**, in order to clearly portray the profile of each section. Each bolt section has a distinct relationship, indicating that the in situ shear bond is not consistent along the bolt. This was caused by several factors such as plastic film gloving and entrapped air bubbles due to poor resin mix times. All the load-displacement curves can be classified into three types, which are shown in **Fig. 5c**. For Type 1, the loads increase rapidly to the peak loading point, followed by a sudden decrease, and in the end a steady and lower residual load was maintained. Type 2 essentially belongs to Type 1, the difference between these two being that loads of Type 2 increase rapidly to the first peak point and subsequently increase to a higher peak point before decreasing. Type 3 increases slowly to the peak load. Types 1 and 2 have higher shear bond stiffness than Type 3.

For Bolt 3, Sections A–F belong to Type 1, Section G belongs to Type 2, and the remaining sections belong to Type 3. By closely examining the steel tubes and rockbolts after the push tests (the photos are shown in **Fig. 6**), it is found that: (1) resin covered the majority of the surface of Sections A–G bolts after push tests, indicating that bolts shear off resin between ribs. The possible resin shear position is illustrated by the red dashed line in **Fig. 7**; (2) Less resin was found on bolts H–O. Resin was possibly sheared along the yellow dashed line as shown in **Fig. 7**. This explains why Sections A–G have a higher bond stiffness than Sections H–O; (3) Section A has the lowest shear bond capacity, which was caused by the unmixed resin and film gloving (illustrated in **Fig. 6**).

The three types of load-displacement behaviors are found in other bolts. For other bolts, each section also has its distinct load-displacement relationship, which is the same as with Bolt 3. The results vary from bolt to bolt as, but in general, each group (Bolts 1 and 2, Bolts 3 and 4, Bolts 5 and 6, Bolts 7 and 8, and Bolts 9 and 10) has similar load-displacement relationships.

BOLTS 1–12

The above section shows the load-displacement curves of Bolt 3. In the following sections, the maximum push load is used as the bond strength for each bolt section and is plotted versus the bolt

FIG. 5 Load-displacement relationships of 100 mm cut sections for Rockbolt 3. (a) all sections, (b) The top of Bolt 3, (c) The middle of Bolt 3, and (d) the bottom of bolt 3.

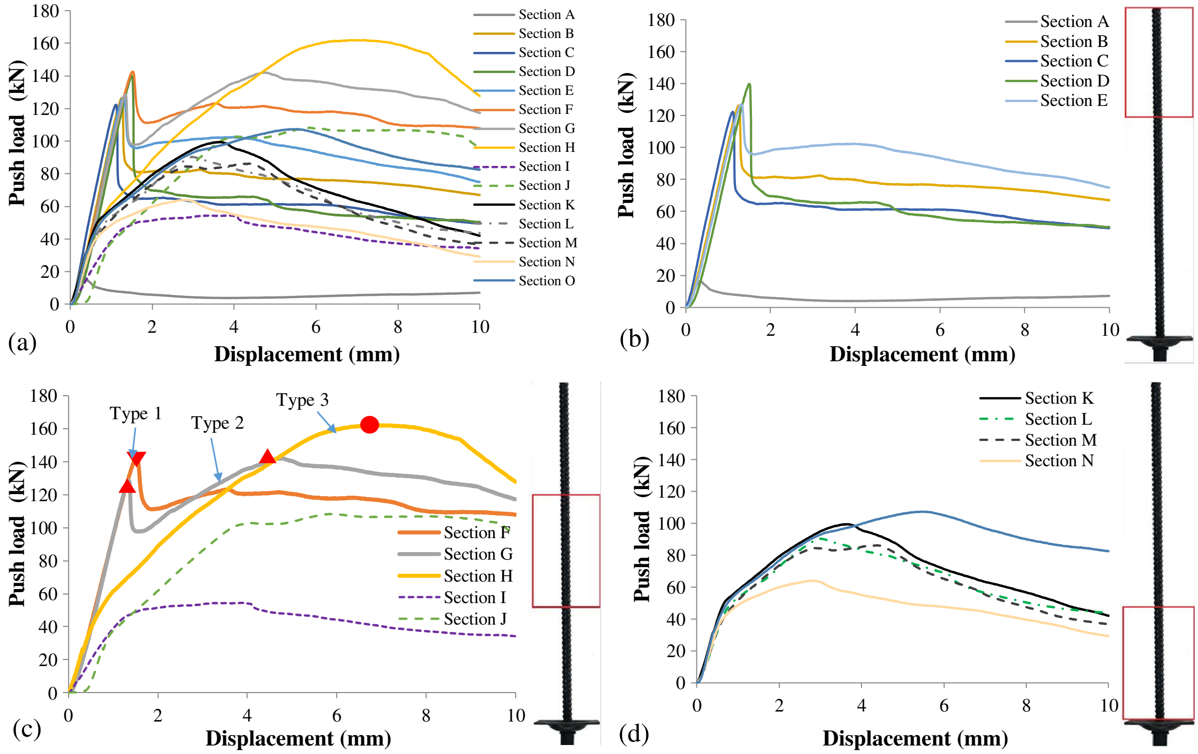


FIG. 6 The photos of bolt sections after push tests.

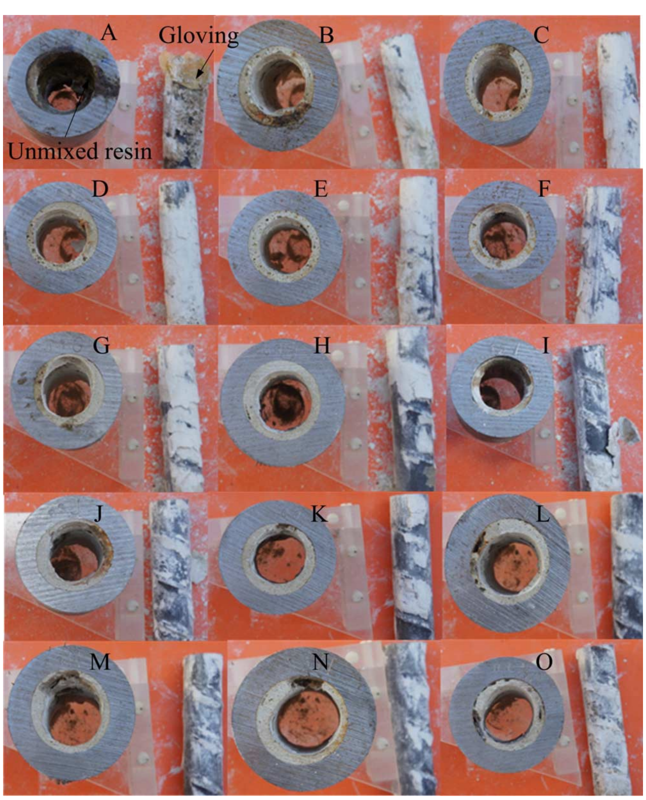
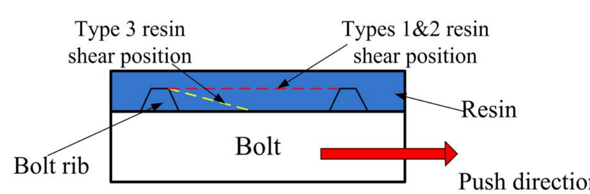


FIG. 7 The resin shear positions of Types 1, 2, and 3.



section position for Bolts 1–12. These bolts are divided into six groups: Bolts 1 and 2, Bolts 3 and 4, Bolts 5 and 6, Bolts 7 and 8, Bolts 9 and 10, and Bolts 11 and 12, based on the installation procedure such as spin time as shown in **Table 1**.

JBX Bolts 1 and 2

Bolts 1 and 2 were installed using a spin time of 10 s at 420 r/min into the back of the hole, and were spun for an additional 4 s at 450 r/min at the back of the hole. The maximum push test loads versus the bolt position for the two bolts are shown in **Fig. 8**. The average load of Rockbolts 1 and 2 was 107 kN and 105 kN, respectively.

The front sections (A and B) of Bolts 1 and 2 had lower loads, which was caused by the moderate to excessive film gloving. Due to the machining difficulties of the rifles in the 1.7-m steel tube, Section I of all bolts was found to lack threading in the internal

FIG. 8 Maximum push loads of bolt sections along Bolts 1 and 2.

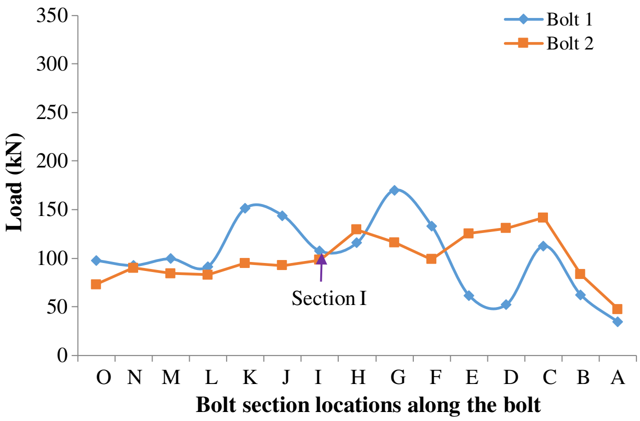
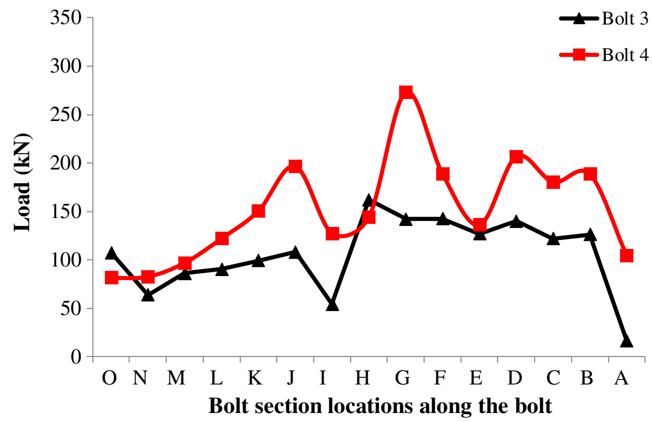


FIG. 10 Maximum push loads of 100-mm-long cut sections along Bolts 3 and 4.



wall of steel tubes, or to contain no threading at all, which could explain the low bond strength of Section I for Bolt 2. Sections L, M, N, and O near the collar end had the least film gloving; however, air bubbles were detected in the resin annulus. Because these two tests used different bolts, resin capsules, and spin times in the installation, Bolts 1 and 2 are not compared to the other tests.

It is worth noting that adjacent Sections E and G of Bolt 1 had push loads of 170 kN and 61.75 kN, respectively. The gloving significantly influenced the shear bond strength of these bolt sections. As can be seen in Fig. 9, there was a lot of plastic film wrapped around the bolt for Section E, which led to a low push load (only 61.75 kN). In comparison, Section G, which was only 20 cm away from Section E, had a good grouting condition, and the resin between the bolt ribs were completely sheared off as shown in Fig. 9c, which resulted in a high push load (170 kN). For the same reason, Section H, which was only 10 cm away from Section G, had a low push load due to plastic gloving.

JX Bolts 3 and 4

JX bolts 3 and 4 were spun for 9 s at 420 r/min to the back, and spun for 3 s at 450 r/min at the back. Fig. 10 shows the maximum push loads for Bolts 3 and 4. The average maximum push load of Bolts 3 and 4 was 137 kN per section, which was defined as the baseline benchmark strength. Bolts 3 and 4 used the current Australian Spin and Hold method. Their results are used to compare with those of Bolts 5–12, which used the same bolt and resin material as Bolts 3 and 4, with the objective to study the effect of different installation procedures on bolt performance.

FIG. 9 Post-tests of Sections E, G, and H for Bolt 1.

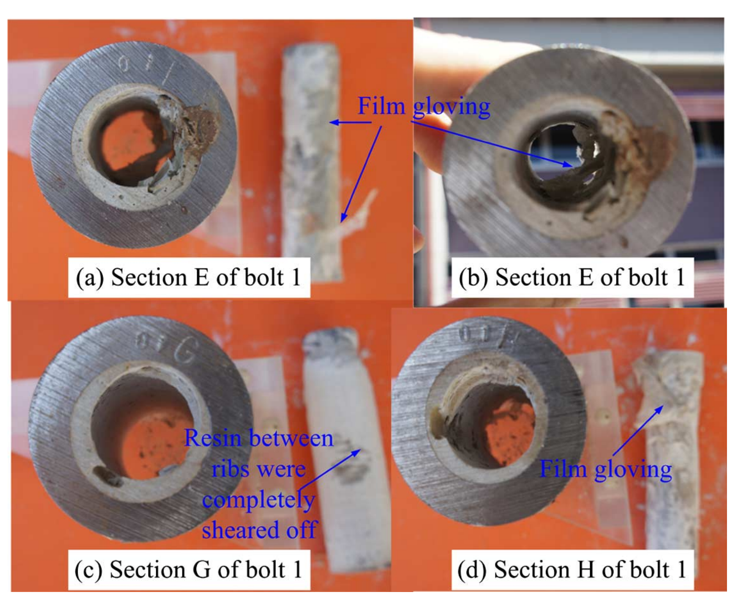
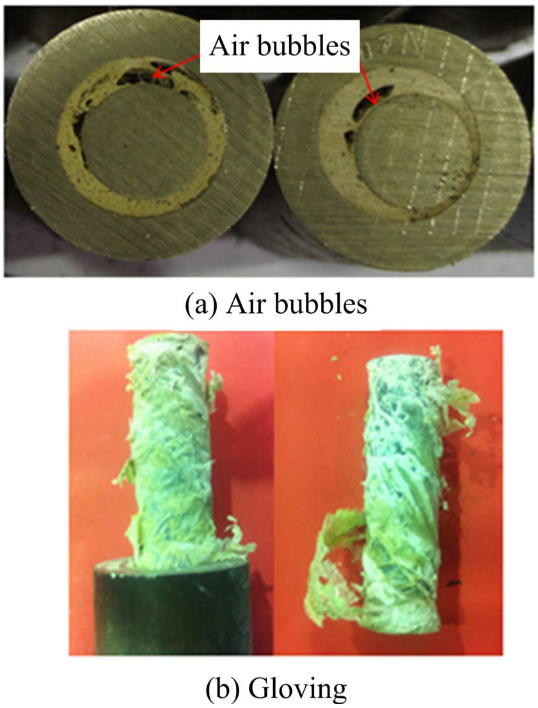


FIG. 11 Air bubbles and gloving.



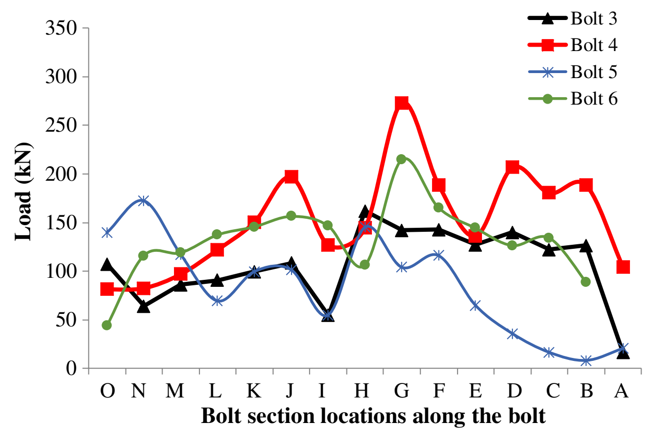
The test results of Bolt 3 was discussed in the previous section. The gloving was found primarily in Section A and fewer air bubbles were detected within the resin annulus. The low push load of Section I was caused by the lack of threading in the tube as indicated before. For Bolt 4, the low push loads of Sections E, M, N, and O were due to the presence of excessive gloving and air bubbles, which are shown in **Fig.** 11.

JX Bolts 5 and 6

Bolts 5 and 6 were spun for 6 s with a rotation speed of 100 r/min to the back of the hole; at the back of the hole they were put for another 6 s at 100 and 450 r/min, respectively. The maximum push loads of Bolts 5 and 6 are shown in **Fig.** 12.

Bolt 5 had the average maximum push load of 85 kN, much lower than the baseline benchmark strength of 137 kN. Sections A, B, C, and D of Bolt 5 had excessive film gloving, which completely covered the bolt and reduced the bond strength. Section I had a lower push load in comparison to the adjacent sections, which was due to the fact that the steel tube did not have internal threading. Bolt 6 had the average maximum push load of 139 kN, which was similar to the baseline benchmark strength of 137 kN. An overwhelming good quality of Bolt 6 was due to the higher rotation speed at the back of the hole. Excessive gloving was confined mostly in Sections A and B for Bolt 6. It can be seen in **Fig.** 12 that Bolt 6 had a similar bond strength to Bolts 3 and 4, while Bolt 5 had a lower bond strength, especially at the front Sections A, B, C, D, E, and F.

FIG. 12 Maximum push loads of cut sections along bolts 5 and 6.



It can be concluded that the insufficient rotation at the back of hole may have resulted in the low bond strength of rockbolts.

JX Bolts 7 and 8.

Bolts 7 and 8 were spun with a rotation speed of 420 r/min from the start to stall. Although similar spin times at the back of the hole were used for two bolts (28 plus 35 s for Bolt 7, and 29 plus 33 s for Bolt 8), Bolt 7 had the average maximum push load of 85 kN, while Bolt 8 had the maximum load of 139 kN. It can be seen in **Fig.** 13 that, with the use of the Spin to Stall technique, Bolts 7 and 8 produced similar shear bond strength to Bolts 3 and 4.

But there still exists the possibility that the high rotation speed from the start to stall overmixed the resin and weakened the resin strength. Hence, less spin time and slow rotation speed during the Spin to Back stage was used in Bolts 9 and 10.

JX Bolts 9 and 10

Bolts 9 and 10 were spun to back for 6 s at 100 r/min and then were spun until the drilling machine stalled, using a rotation

FIG. 13 Maximum push loads of cut sections along Bolts 7 and 8.

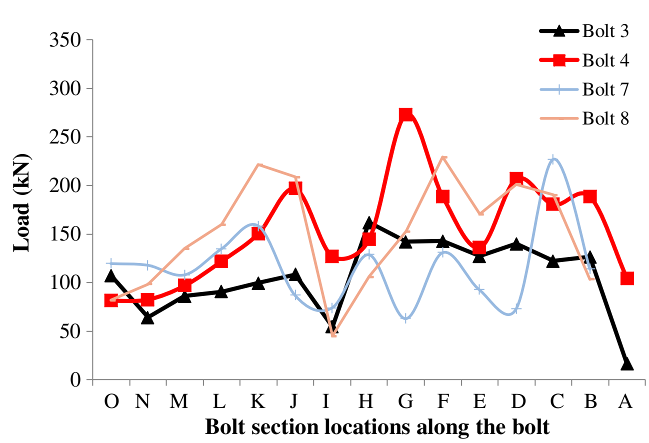
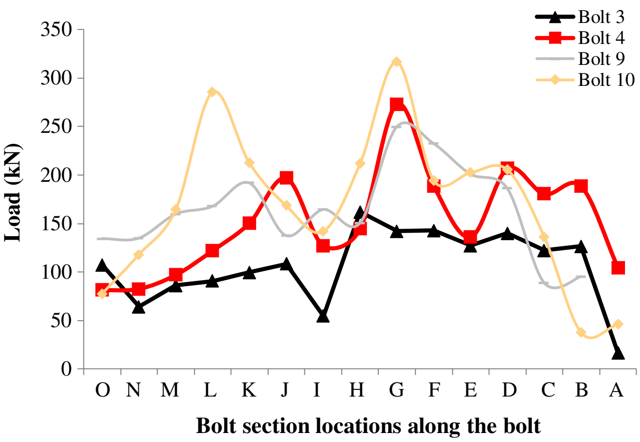


FIG. 14 Maximum push loads of sections along Bolts 9 and 10.



speed of 450 r/min. The maximum push loads of Bolts 9 and 10 are shown in **Fig. 14**. For Bolts 9 and 10, moderate/excessive film gloving was discovered in Sections A, B, and C, as well as in Sections N and O, which explains why these sections had weak bond strength.

As can be seen in **Fig. 14**, Bolts 9 and 10 behaved slightly better than Bolts 3 and 4. It can be concluded that the Spin-to-Stall method, in general, was as good as the Spin and Hold method (i.e., Bolts 7 and 8), or slightly better than the Spin and Hold method (i.e., Bolts 9 and 10) when slow mixing speed was used in the spin to back stage to prevent over-mixing of resin.

JX Bolts 11 and 12

According to the results of Bolts 9 and 10, it was found that the slow rotation in the Spin to Back stage could improve bolt performance. In contrast, Bolts 11 and 12 were pushed to the back of holes with no rotation, followed by the high rotation speed of 450 r/min until the machine stalled.

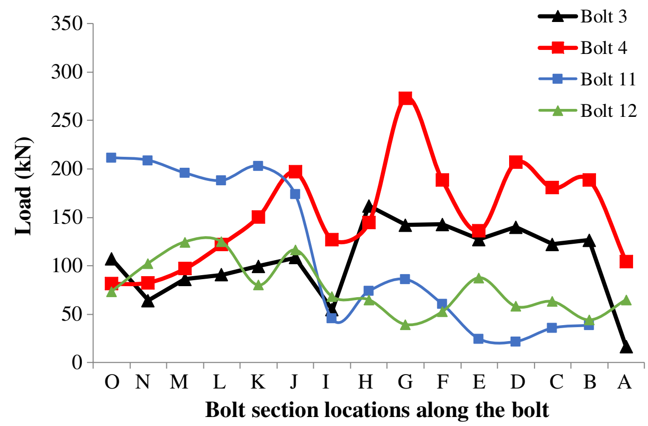
The results of Bolts 11 and 12 are shown in **Fig. 15**. Bolts 11 and 12 had low bond strength for Sections A–G, in comparison to Bolts 3 and 4. The observation after testing shows that the lack of rotation has led to excessive capsule film gloving in the upper half of the bolts, which significantly decreased the shear bond strength of the rockbolts.

All twelve steel tubes had no/minimal internal threading at Section I as shown in **Fig. 16**, which was caused by a miscalculation when manufacturing the tubes. Tubes in future tests should be threaded throughout the entire length.

ADDITIONAL FOUR BOLT TESTS

The top part of most bolts had less bond strength due to film gloving. An additional four bolts were studied to further investigate the bolt installation and gloving with respect to bolt spin duration, the influence of over drilling on gloving reduction, and the Spin-to-Stop and Spin-until-Pin-Break methods. The

FIG. 15 Maximum push loads of cut sections along Bolts 11 and 12.



installation details are given in **Table 2**. These bolts were installed using a hydraulic drill with a rotation of 400–500 r/min. For Bolt 3, a 50-mm space was left between the top end of the bolt and the cap of the tube as an overdrill to allow resin sheath accumulation in the space unoccupied by the bolt end. Bolt 4 was spun until the pin broke at the back of the hole. These recovered bolts are shown in **Fig. 17**. Following a similar procedure of the previous tests, these four bolts were cut into 100-mm sections and push tested. The maximum push loads of sections of the four bolts are shown in **Fig. 18**.

It was observed that film gloving occurred mostly in the range of 400–500 mm in the upper part of bolts (i.e., Sections O–S for these four bolts). Note that Section A is the bolt collar end for this batch of bolts. Bolt 3 had a higher shear bond strength than the other bolts at the top part, as highlighted in the black rectangle in **Fig. 18**. The residual plastic capsule film was accumulated in the overdrilled borehole section and is shown in **Fig. 19**.

FIG. 16 Unrifled middle section of the steel tube.

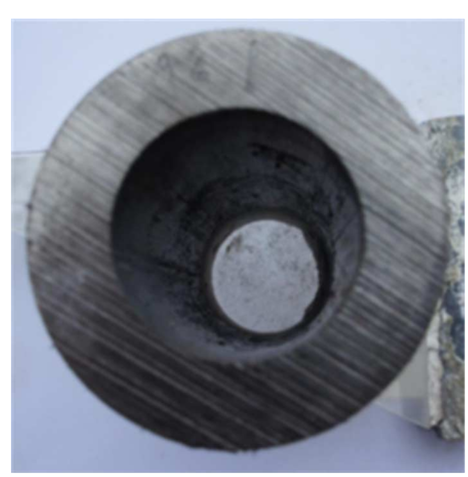
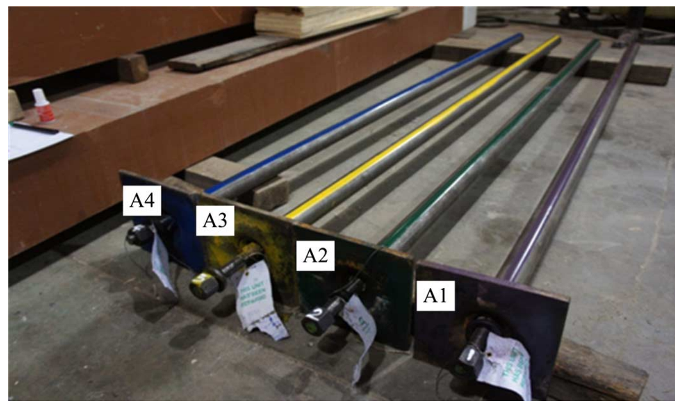


TABLE 2 Bolt installation details of second batch of rockbolts.

Bolts	Spin-to-Back time (s)	Spin-at-Back time (s)	Notes
Bolt A1	7	7	NA
Bolt A2	10	4	NA
Bolt A3	7	7	50 mm overdrilled at the top of bolt
Bolt A4	7	38	Spin until pin breaks

FIG. 17
The second batch of encapsulated bolts installed in steel tubes.



This overdrill space reduces film gloving at the top of the bolt and increases its load capacity. It was also found that Bolt 4, with the use of the Spin to Stall method, had slightly less bond strength than the other three. Apparently, over-spinning resin at back (38 s for Bolt 4 at back) reduced the resin strength.

The second batch of encapsulated and tested bolts demonstrated that overdrilling has contributed to the effectiveness of the encapsulation because the excess gloving ended up accumulating in the 50-mm overdrill space in Bolt A3, as demonstrated in Fig. 19. As a result, the top end of the overdrilled bolt has higher bond strength than the other three bolts in this batch that went without overdrilling.

Discussions

The objective of this study was to investigate the effects of the bolt installation procedure and the effects of the film gloving on bolt

FIG. 18
Maximum push loads of four rockbolts installed in steel tubes (Aziz et al. 2014).

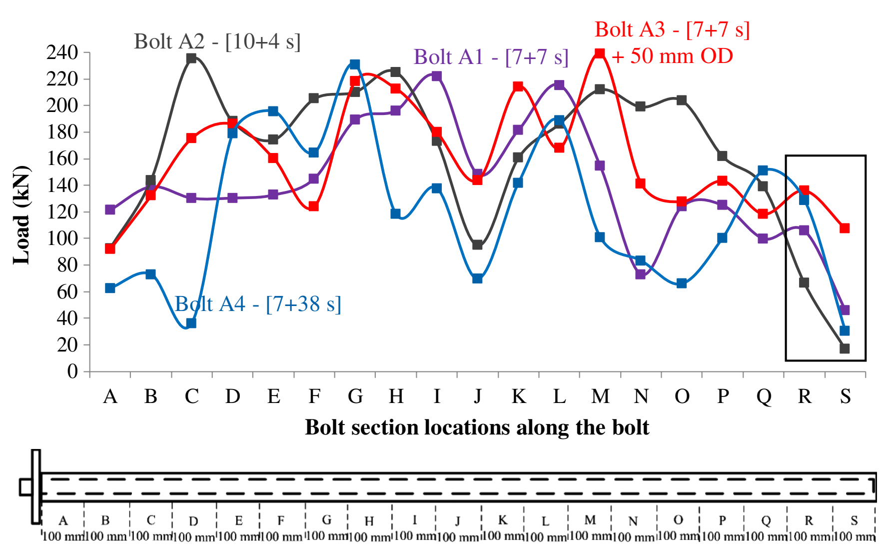


FIG. 19 The gloving film found in the overdrilled hole (Aziz et al. 2014).

behaviors. In this study, steel tubes/pipes were used to represent the confinement of the rock masses in the field. Push tests instead of pull tests were adopted in the experiments. The limitations of this study are discussed in the following:

Factors such as the confining stress of the host rock materials and the bolt-grout and grout-rock interactions could affect the bonding characteristics of fully grouted rockbolts. The internal surface of boreholes drilled in the rock mass had irregularities, which generated friction in the grout-rock interface. In this study, steel pipes were used to model the confinement of the rock masses. The internal walls of the steel pipes were threaded (2-mm thread). The threaded internal walls of the steel pipes represent the uneven internal surface of boreholes, which provides high friction at the grout-pipe interface. It can be seen from **Fig. 6** that, in most cases of push testing, the grout-pipe interfaces were not damaged (the resin was left in pipes after testing). The use of pipes mainly affects the bolt behaviors in two ways:

1. Steel pipes have much higher stiffness (200 GPa) compared to the mudstone hosts rock (7 Gpa), and thus pipes provide higher confinement to rockbolts than the boreholes. The obtained push load versus displacement might be higher than those of the in situ bolt tests.
2. Bolt failure might occur at the grout-rock interface in the field, which depends on various factors such as surrounding rock properties, the used grout quality, and borehole drilling quality. However, in our steel tube push tests, bolt failure occurs only at the bolt-grout interface due to the high friction between resin and borehole.

In addition, the testing method could also impact the bolt loads. The push tests rather than the pullout tests were adopted in this study. We conducted the push tests because we could not undertake pullout testing. Pull testing would mean sacrificing a huge length of the bolt for gripping and pull testing. With push testing, however, it was possible to test every millimeter of the bolt. Generally, the push tests might offer a higher load-bearing capacity than the pullout tests (Aziz and Jalalifar 2005). The authors assume that the main difference between the push tests and the pullout tests lies in the fact that in the pullout tests, the steel rebar was in tension and elongated, whereas in the push tests, the steel rebar was in compression. For the push tests, crushed resin particles generate resistance ahead, which is not the case in pullout tests. Hence, higher loads were generated in push tests. However, this is a complicated interaction process and further verifications need to be performed. The other limitations of this study are as follows:

1. There is a wide scatter in the push load data in this study, which is attributed to the varying installation quality (i.e., different resin cavities and plastic gloving wrapped around the bolt). This study therefore demonstrates the variation of the inconsistency and competency of full column encapsulation along the entire bolt length, showing the varying push loads along the bolt. Moreover, the central section of each bolt has a very low push load because the inside wall of the central section was not threaded.
2. Short embedment length (100 mm) was used in this study to evaluate the bonding characteristics along the full encapsulation length. The obtained results might not necessarily represent the behaviors of long bolts (more than 1-m long encapsulation); hence, these results should be used with caution.

Nevertheless, the test in this study was a comparative test irrespective of loads generated. The above limitations have little influence on the conclusions drawn in this study.

Summary

This study investigates the effects of the installation procedure on the bond characteristics of fully grouted rockbolts. The bolts were installed in steel tubes using the installation technique employed in underground mines. The steel tubes with the bolts installed inside were recovered and transferred to the rock mechanics laboratory in UOW. They were sectionalised into 100-mm pieces and push tested. The findings from the laboratory rockbolt push tests are as follows:

- The bond strength varied significantly along the rockbolts. The top part of most bolts had less bond strength, which was due to film gloving and unmixed resin. Each bolt section had a distinct load-displacement curve.
- Less spinning in the bolt installation led to weaker bond strength and reduced the bolt performance (Bolt 5 versus Bolt 6). No spinning when the bolt was pushed to back (Bolts 11 and 12) led to unmixed resin, excessive gloving,

and a large amount of air bubbles, which significantly weakened the resin strength.

- Limited test results suggest that the Spin to Stall technique generated an equivalent (Bolts 7 and 8) or better (Bolts 9 and 10 bond strength, less spinning rotation was used in the Spin to Back stage) when compared with the Spin and Hold method (Bolts 3 and 4). However, according to the additional four bolt tests, the Spin to Stall technique may over-mix the resin and reduce the resin bond strength. Further field tests need to be conducted before any realistic conclusions can be drawn.
- Overdrilled holes reduced the capsule film gloving in the top of bolts and improved the bolt performance. The experimental findings in this study could closely describe the practical behavior of rockbolts in the field, as these bolts were installed following the standard installation procedure.

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